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DEVELOPMENT AND DEMONSTRATION OF AN AGENT-ORIENTED INTEGRATION METHODOLOGY

Kaman Sciences Corporation

Carrie Kindler, Ray DeLuke, John Rhea, and John C. Kunz

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APPROVED: Craig S. Anken

CRAIG S. ANKEN
Project Engineer

FOR THE DIRECTOR: John A. Graniero

JOHN A. GRANIERO, Chief Scientist
Command, Control & Communications Directorate

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Carrie Kindler, Ray DeLuke, John Rhea, and John C. Kunz

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Kaman Sciences Corporation
Griffiss Business & Technology Park
775 Daedalian Dr.
Rome, NY 13441-4909

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The purpose of this project was to develop and to successfully demonstrate a methodology for creating a problem-solving expert system environment within which two or more expert systems, addressing different facets of a common problem, work together in synergy to solve that problem. The subject problem was taken from the power utility domain and addressed the following issues associated with power plant operations: Diagnosis and identification of imminent or actual hardware failure, planning and scheduling of maintenance and repair of failed or failing equipment, and establishing metrics of cost-effectiveness and risk associated with different preventative maintenance options or scenarios.

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ABSTRACT

The purpose of this project was to develop and to successfully demonstrate a methodology for creating a problem-solving expert system environment within which two or more expert systems, addressing different facets of a common problem, work together in synergy to solve that problem. The subject problem was taken from the power utility domain and addressed the following issues associated with power plant operations:

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- Planning and scheduling of maintenance and repair of failed or failing equipment
- Establishing metrics of cost-effectiveness and risk associated with different preventative maintenance options or scenarios.

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1 EXECUTIVE SUMMARY

In the past decade, The Electric Power Research Institute (EPRI) has sponsored numerous research projects which have culminated in the development and deployment of application-specific expert system (ES) tools that were designed to enable plant engineers and technicians to better and more efficiently perform their functions. These expert systems have been rather narrowly focused on particular aspects of power plant subsystem health monitoring and diagnostics. However, such stand-alone software tools have yet to be further integrated into a comprehensive facility system that would be able to provide utilities with end-to-end expert system support. This is the goal of this project.

In the early nineties, EPRI and Stanford University's Center for Integrated Facilities Engineering (CIFE) developed an integrated expert system aimed at addressing the still narrow issue of power plant boiler feed pump subsystem operations from an integrated perspective that focused on the diagnosis, planning, and value assessment of maintenance and repair. This system, called the Intelligent Real-Time Maintenance Monitor and Planner (IRTMM), was developed to run on a single Sun Microsystems workstation. For EPRI , the IRTMM represented a first attempt at integrating different expert system functions into a single tool. The goals of this project were to be met by building on the legacy of IRTMM and enhancing it's functionality through the use of the Advanced AI Technology Testbed (AAITT)[1,2] located at Rome Laboratory. This project would break new ground in addressing issues of ES tool integration as follows:

(1) To design and develop an architecture, using the AAITT, to permit multiple ES modules, de-integrated from the original IRTMM, to run on multiple platforms, using the Distributed Processing Substrate (DPS) architecture for communications and interaction.

(2) To enhance the conventional blackboard (BB) system model to enable the interaction of multiple ES modules, running on different AAITT platforms, to communicate and to operate synergistically in a global problem-solving configuration. This distributed BB, or "facilitated autonomous agent" architecture is based on Stanford's NSF and ARPA sponsored pioneering work in Agent Communications Language (ACL)[3] and facilitator design.

(3) To demonstrate the functionality of the distributed ACL-based architecture by implementing the integration of an EPRI-developed ES module, not intended to operate within the IRTMM framework, into the AAITT running within the distributed agent (ES) system design.

There were several anticipated benefits to be derived from this project as follows:

(A) At the outset of this effort EPRI was developing, through it's Monitoring and Diagnostic (M&D) Center in Philadelphia, a distributed architecture designed to allow inter-operation of numerous EPRI-developed software packages for power plant operational support in areas such as process monitoring and maintenance planning. However, as then configured, this architecture (i) relied exclusively on the user to call the appropriate programs and effect any desired data exchanges; and (ii) was not designed to address integration of ES components.

The system, known as the Operations and Maintenance (O&M) Workstation, would be a unified source of operational and diagnostic information for fossil-fueled power plants. The system would not operate as an integral whole, but would rather permit the O&M personnel to call on subprograms to aid them in their decision making.

The architecture for the O&M Workstation was implemented within EPRIWorks[4], a communications environment developed by EPRI to enable the development of standardized, portable software applications in a TCP/IP or DECNet protocol environment.

Rome Laboratory's AAITT provided the fundamental hardware, operating system and communications facilities for expert system integration, in addition to tools for constructing high level integration structures. The successful development of the AAITT-based IRTMM extension would provide EPRI with an integration methodology, using a facilitated autonomous agent architecture, to permit synergistic and ES-to-ES interaction.

(B) This effort would provide a distributed blackboard architecture for synergistic problem-solving by disparate ES modules.

2 PROJECT TEAM

This project was executed by a team comprised of the Central New York office of Kaman Sciences Corporation now located in Rome, NY; Syracuse University located in Syracuse, NY; and Lockheed-Martin Advanced Technology Laboratory (formerly Martin Marietta Labs) located in Morristown, NJ. The role of each team member is defined as follows:

Kaman Sciences Corp.

- Prime contractor responsible for project management and technical oversight.
- Execute the porting and integration of IRTMM derived and selected Agent software to the AAITT

Stanford University

- Unbundle IRTMM & develop Agents using the Agent Communication Language (ACL). This Agent software would provide Situation Assessment, Planning, and Value Analysis.
- Development of performance metrics for the system.
- Performance of Agent-Architecture sensitivity studies.

Lockheed-Martin Advanced Technology Laboratory

- Provide training in the use of the AAITT and the Distributed Processing Substrate
- Provide assistance to Kaman in the integration of the IRTMM and the Agent software into the AAITT environment

3
TECHNICAL APPROACH

The project proposal consisted of eight principal tasks designed to achieve the program objectives identified earlier in this report. At an early stage in the project several adjustments to the project work plan were proposed by the project team, approved, and adopted. Three issues suggested that adjustments to the workplan were appropriate. These were:

- The desirability of substituting a more relevant EPRI product in place of the VIAD expert system originally planned for use in the project. VIAD was not in wide use in the utility industry and did not offer an on-line system. The timely availability of EPRI's newly developed diagnostic system for power plant boiler feed pumps (BFP) provided a much more relevant and interesting tool to the project.

- Emergence of commercial operating systems such as Windows NT, OS/2, and later generations of UNIX address many of the problems of providing communication mechanisms between disparate software modules.

- EPRI's focus on a model-based paradigm for integration of power plant software systems. EPRI developed the Operation and Maintenance Workstation, an object-oriented database for integrating and managing plant information that is based on a systems model of the power plant. EPRI also initiated an exploratory project to develop an integrated knowledge framework for power plants based on the human processes involved in plant operation and maintenance, and their relationships to plant systems and hardware. These developments, as well as generic technical development such as the movement toward industry-specific foundation classes for object-oriented software development, suggested focusing on a knowledge model as the bsis for facilitating knowledge integration among disparate software modules.

Table 1 shows a breakdown of the changes in each task and the rational behind the changes.

Table 1 - Work Plan Adjustments

Task #	Task Description	Changes	Rational
1	Unbundle IRTMM modules	No change	
2	Design & implement "facilitator" based integration.		
2.a		Develop a state-of-the art report on Integration and Interoperability of Multiple Applications, reviewing alternative technical approaches. Report to be published as a DoD Data and Analysis Center for Software (DACS) State-of-the-Art Report (SOAR) and, if desired by EPRI, as an EPRI research report	Such a report is timely and provided important guidance to the remainder of the project, as well as to future Rome Lab and EPRI efforts in this area
2.b		Create 2 proof-of-concept integration architectures integrating 2 Stanford IRTMM applications. One architecture to be a "model agent" facilitator based on a plant model from Stanford IRTMM	This would provide a basis for evaluation of model agent architecture
3	Design integration metrics	Substitute informal comparison of alternative architectures for formal metrics. Delete this task.	Use of formal metrics would be premature. Effort would be better spent to increase emphasis on architecture options, including State-of-the-Art Report and model-based facilitator
4	Port EPRI VIAD to AAITT	Substitute EPRI BFP system for VIAD	BFP system is more relevant and more representative of modern power plant diagnostic software.
5	Port IRTMM modules to AAITT	No change	
6	Integrate IRTMM modules on AAITT using "facilitator" architecture	Integrate using two alternative architectures: (i) direct communication between modules using AAITT wrappers as interface; and (ii) using model agent facilitator.	This provided a basis for evaluation of model agent architecture.
7	Evaluate "facilitator" architecture	Perform informal evaluation as part of AAITT demonstration of Task 6 architectures.	Same as Task 3
8	Technology transfer	Eliminate EPRI seminar presentation. Technology transfer will be through State-of-the-Art Report, Task 6 demonstrations, and Final Report. Appropriate information will also be provided to EPRI M&D Center for use in O&M Workstation development and various utility events.	Project results would be at too early a stage for direct technology transfer to utility industry.
9	Project management	Additional sub-contract to EPRI M&D Center for support for BFP system	Same as Task 4

- **Task 1 - Unbundle IRTMM Modules**
  The IRTMM SA, PL and VA were designed to be modular, but they are implemented in a tightly coupled architecture in which they share access to the plant model. We will give each a copy of the plant model and isolate the message passing for passing control and, as necessary, add message passing routines to update information for other modules. The IRTMM modules have been implemented using modern object-oriented programming techniques. They now communicate using inter-module message passing supported by the underlying Kappa tool. The message passing is already encapsulated and separated from the main reasoning procedures of each module. The task is necessary but not difficult or of research interest.

  This task remained unchanged and was completed as planned during the first quarter of the project.

- **Task 2 - Modify Control Structure Of IRTMM Modules**
  This task will identify and prototype two or three alternative architectures for integration of multiple applications. The focus in defining these architectures will be on mechanisms allowing disparate applications to identify relevant information from other applications and to interpret and apply it appropriately ("semantic translation"). Thus, the emphasis will be on semantic translation among multiple applications, rather than on the mechanical aspects of inter-application communication. This task work has two sub-tasks:

  2.a Preparation of a research report on the state-of-the-art in Integration and Interoperability of Multiple Applications. This report will be produced by Stanford CIFE and reviewed by Kaman. It will provide a theoretical discussion of interoperability issues, reviewing past R&D approaches (including AAITT and EPRIWorks), current commercial approaches and new research technologies. The separate issues of data exchange and semantic translation will both be discussed and related. A case example based on IRTMM modules will be presented in detail. The intended audience for this report is a journal in the engineering literature, however, the report will be formatted and appropriate for distribution as an EPRI report and a DoD Data and Analysis Center for Software (DACS) State-of-the-Art Report (SOAR). If need be, the DACS is willing to perform any special formatting necessary to produce the SOAR.

  2.b Proof-of-concept demonstrations of two or three integration architectures allowing 2 applications derived from the EPRI/Stanford IRTMM to interact. Candidate architectures include (i) direct communication (mediated by a "wrapper" interface); (ii) communication through an intermediary "facilitator" to mediate data communication; and (iii) communication through a "model agent" which is essentially a facilitator based on a model of the shared knowledge domain -- in this case, the power plant.

In each case, the two applications will be given a "wrapper" to manage the communication. For direct communication, the wrapper needs to incorporate both data communication protocols and semantic translation. For facilitator-mediated translation, the wrapper incorporates data communication protocols and the facilitator does ad-hoc semantic translation. For "model agent" communication, a plant model module will include semantic translation methods. The architectures will be designed and prototyped by Stanford CIFE using IRTMM modules and a "stub" diagnostic application representing the EPRI Boiler Feed Pump (BFP) system.

The 2.a SOAR was developed by Stanford submitted and approved by Rome Laboratory and by EPRI.

The 2.b proof of concept effort was completed in the form a paper prepared by Stanford entitled "Summary of Two Integration Architectures". This paper may be found in Appendix A of this report.

- **Task 3 - Develop Metrics To Measure Performance**
  This task was eliminated in favor of increasing the effort on the evaluation of alternative architectures in the Task 2 State-of-the-Art Report.

- **Task 4 - Port EPRI VIAD To The AAITT**
  The EPRI Boiler Feed Pump (BFP) Expert System will be substituted for VIAD. This will involve increased effort to integrate the BFP system with the other modules. However, it is believed that the additional effort is justified by the resulting improvement in the relevance of the project results to power industry applications.

  To integrate the BFP system with the other modules in the AAITT demonstration, EPRI's Monitoring & Diagnostic Center (EPRI M&D) will provide a Database Driver application for installation into the AAITT that will interface to the BFP system running on a personal computer under Windows. EPRI M&D will also provide a test set of data to allow Kaman to produce the diagnostic problems discussed above and will provide a capability within the BFP system to simulate real-time processing of data.

  At the outset of this project problems with the use of VIAD as the chosen vibration advisor were identified. The VIAD expert system was not in wide use in the utility industry, and was not an on-line system. These shortcomings reduced VIAD's relevance to the goal of the project: to demonstrate an advance architecture for real-time integration of knowledge-based systems. After initial scheduling problems regarding software availability and difficulties in bringing up the AAITT system were resolved the project team determined that a technically viable alternative to VIAD would be EPRI's Boiler Feed Pump (BFP) vibration advisor. The use of the BFP ES provided an up-to-date and relevant tool better suited to the needs of EPRI.

The use of the BFP software required project support from DHR Technologies in the conversion of the Rotating Equipment Expert System (REX) for use on AAITT. REX is the commercial version of the BFP system. The REX software was successfully converted and delivered by DHR Technologies.

- **Task 5 - Port Selected IRTMM Modules To The AAITT**
  This activity serves the objective of developing a state-of-the-art integration architecture for use at AAITT. Stanford will assist Kaman in doing the port. The only technical issue we see is integrating the ACL-based agents with the DPS communications protocol of the AAITT. As part of this activity, Stanford will also train Kaman and Rome Laboratory staff in use of the IRTMM system so that they can do demonstrations, run test cases, and perform what-if studies with data provided by other sources available in the AAITT environment.

  This task remained unchanged from the original proposal. Compatibility issues with the SunOS operating system and the X Windows interface were encountered and slowed progress in the early stages of the project. The problems were overcome and this task was completed.

- **Task 6 - Integrate IRTMM modules on AAITT and demonstrate advanced architecture(s).**
  Alternative architectures developed by Stanford CIFE in Task 2 will be demonstrated by porting them to the AAITT and integrating the BFP system. The demonstration will support the output of the BFP diagnostic application for three common boiler feed pump problem scenarios which have been identified in consultation with EPRI M&D:

  1. *Vibration induced by pump rotor unbalance.*
  2. *Misalignment of the pump and turbine driver shafts.*
  3. *Worn pump bearings.*

  A communication interface will be implemented to allow the other software modules to "understand" the BFP system outputs through the use of the "model agent" and alternative architecture developed by Stanford. Internal modifications to the individual software modules will be avoided or minimized.

  The integration of IRTMM modules on AAITT with direct communication between modules using wrappers as an interface was completed. Integration of modules using model agent facilitators was abandoned in favor of increased effort on Tasks 4 and 8.

- **Task 7 - Perform Agent-Architecture Sensitivity Studies And Evaluate Using Integration Metrics**

An informal evaluation of the "model agent" and alternative architectures prototyped by Stanford will be made on the basis of the demonstration of these architectures on the AAITT.

This task was deleted in order to increased effort on Tasks 4 and 8.

- **Task 8 - Demonstrate And Transfer Technology**
  Technology transfer will be accomplished through:

  1. *Publication of the Report on Integration and Interoperability of Multiple Applications as a State-of-the-Art Report of the DoD Data and Analysis Center for Software (DACS), and through appropriate EPRI channels if desired by EPRI.*
  2. *Continued coordination between this project and the EPRI Boiler Feed Pump System, O&M Workstation, and Integrated Knowledge Framework projects.*
  3. *Making available to the EPRI M&D Center appropriate project information and results for use in their ongoing advisory services to the utility industry.*

A web page summarizing the accomplishments of this project was created and delivered to EPRI for publication on the EPRI home page site. The web page includes a snapshot of the testbed with the three modules integrated. In addition a video was prepared and submitted showing the integration demonstration. A demonstration of the module integration developed within the scope of this project was conducted for Rome Laboratory personnel.

Task 9 - Project Management
Project results shall be documented in a Final Report which shall be published as an EPRI Research Report, which will be made available by EPRI to all EPRI-member utilities. Presentations and meeting shall be conducted at approximately the times specified in the Contract Schedule, at appropriate locations.

4
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3. "Concurrent Engineering Through Interoperable Software Agents," T. Khedro, M.R. Genesereth, and P.M. Teicholz, 1st Conference on Concurrent Engineering: Research & Applications, Pittsburgh, PA, August 1994

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APPENDIX I

Summary of Two Integration Architectures

John C. Kunz

Below is an introduction to two systems and architectures that support software interoperability. This summary is based on the paper "Software Interoperability", EPRI RP9000-32. These examples are described without explicit regard for any underlying software tools used to effect the implemented application integration, and they describe both systems specifically designed for a particular domain as well as more generic ones.

Software Agents

Agent-based software engineering is a formal approach at improving software interoperability. Different "agent" programs communicate with one another using an Agent Communication Language (usually KIF). This interaction is assisted by system programs called "facilitators" that provide services for ensuring agents receive the information they need. Khedro et al describe the use of agents and facilitators in a federation network (see Figure 1) for supporting interoperability in collaborative design in integrated facility engineering.

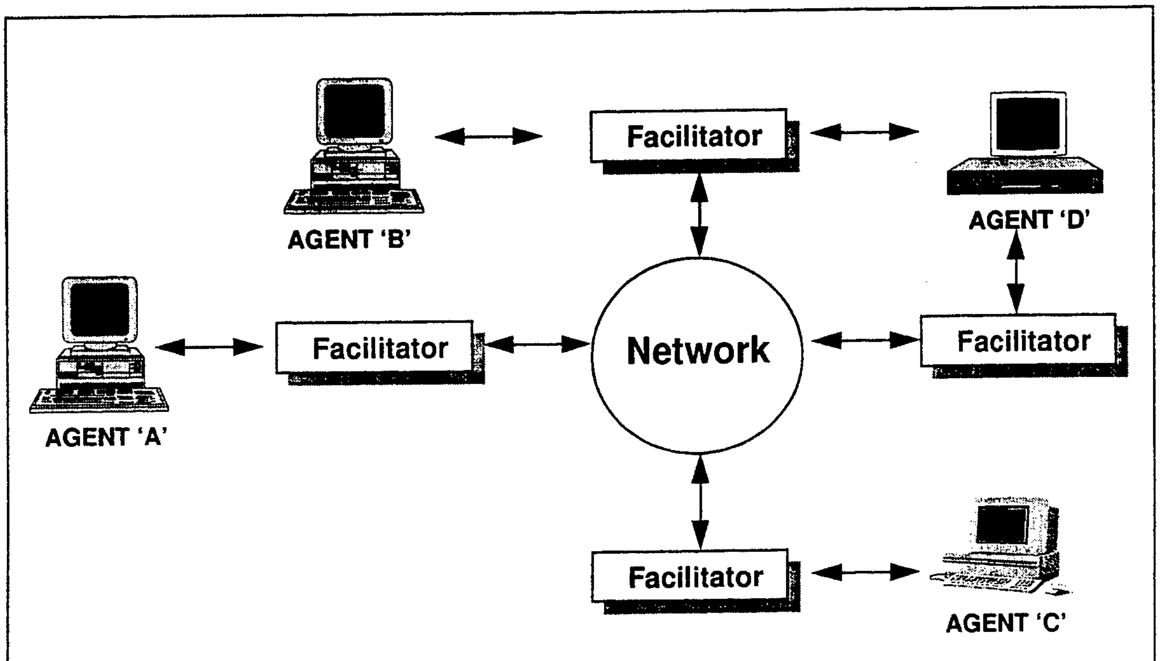


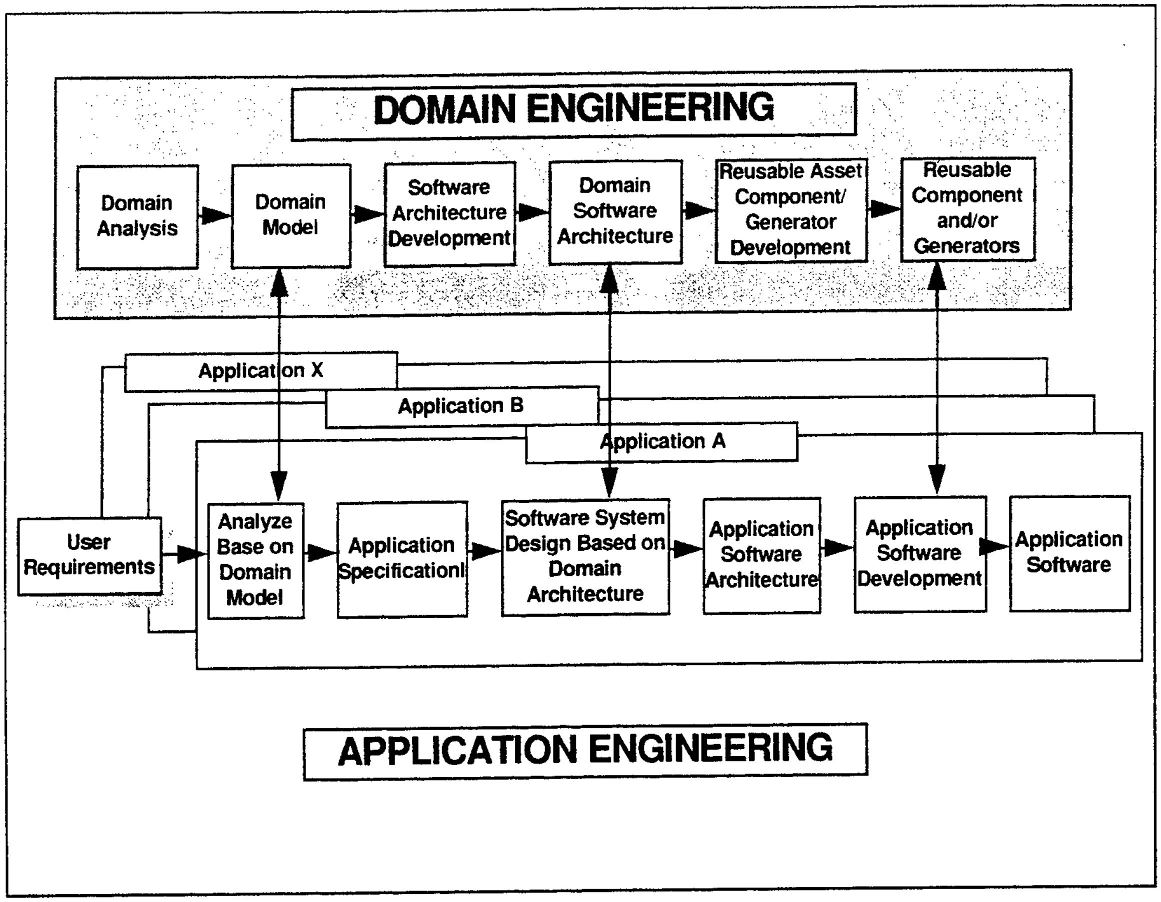
Figure 1: Agent applications interact via facilitators that are responsible for ensuring that agent programs receive the necessary information under a "publish-and-subscription" protocol. Agents exchange knowledge through and interlingua (KIF) that allows for semantic exchange of data based on first-order logic.

PACT (the Palo Alto Collaborative Testbed), an experiment in knowledge integration in concurrent engineering systems using a federation architecture of software agents, is described by Cutkosky et al. This experiment examined the technological and

sociological issues of building large-scale, distributed, concurrent engineering systems. An assumption made was that individual engineering groups prefer to use their own tools and software integration environments. Therefore PACT addressed cooperative development of interfaces, protocols and architecture as well as knowledge sharing among systems maintaining specialized knowledge bases and reasoning mechanisms. The experiment was conducted using 31 agent programs running on 15 workstations, each agent having its own reasoning mechanism and knowledge base. Most of the application software was inherited and required integration into the agent architecture. Conclusions from the experiment were that idiosyncratic design tools contribute to knowledge isolation by preventing designers from sharing design models. A significant finding was that the most difficult task to broad integration of applications was reaching consensus on the ontological commitments that enable knowledge-level communication among applications and that designing an ontology is difficult because it must bridge differences in abstraction and views. The experiment really showed a mechanism for distributed reasoning rather than the sharing of a design model (model sharing in PACT is implicit).

STARS

Boeing, as a prime contractor on the U.S. Advanced Research Projects Agency (ARPA) Software Technology for Adaptable, Reliable Systems (STARS) program, has developed and integrated a demonstration software engineering environment, SEE, that supports a process-driven, domain-specific software development environment. The STARS system separates development into two life-cycle views: domain engineering and application engineering. Multiple applications are supported by a single, ongoing domain engineering effort that develops appropriate reusable software assets based on a shared "domain model". Development of new applications assumes the existence of a reuse library for the domain. A graphical interface model is used for selection of appropriate components. Application developers make engineering decisions based on customer requirements for a specific project, following which the system identifies the applicable reusable components, retrieves them from the library, and adapts them to a specific application. The domain engineering effort is responsible for ensuring the quality of the software components. Boeing has implemented its library in an object-oriented mechanism called ROAMS. Figure 2 shows the logical relationship between the domain and application engineering efforts with regard to the development of applications that can interoperate easily.



Summary Table

This section summarizes the main characteristics of the above approaches to software interoperability in Table 1. Column descriptions are as follows:

- Column 1: Working Demo Implementation (yes/no): An implementation of the methodology has been demonstrated at least as a prototype demonstration.
- Column 2: Shared Database (yes/no): a shared database centralizes the management and storage of data shared by the integrated applications. The column therefore indicates whether the methodologies are centralized or distributed in their management of the model(s) that underlie the software integration mechanism. For example, "Software Agents" can reasonably maintain very different data models, while an integrated framework such as KANON uses a single KB/DB with a query engine and semantic network processor.
- Column 3: Synchronous Communication (yes/no): Tightly-coupled systems inherently require a synchronization of the communication between integrated applications. Loosely coupled systems allow but do not require synchronous communication.

- Column 4: Domain Specific (yes/no): A domain specific methodology has been designed to integrate applications with a limited scope.
- Column 5: Level of Abstraction (data-type/specification/semantic/variable): This column indicates the level of abstraction at which applications share information.
- Column 6: Software Component Model (yes/no): A model base on software components achieves interoperability by controlling the interconnection of various components adapted for use in the integration environment.

Table 1: Summary of a variety of different methodologies and systems aimed at software interoperability.

Methodology	Working Demo	Shared Database	Synchronous communication	Domain specific	Level of Abstraction	Software component model
Software Agents	**Y**	**N**	**N**	**N**	**semantic**	**N**
STARS	**Y**	**N**	**N**	**Y**	**data-type**	**Y**

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